Estimation of Site Core Damage Frequency due to Multi-Unit LOOP: A Case Study on OPR1000 Plants

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1. Introduction

The Fukushima Dai-ichi nuclear accident in 2011 highlighted the importance of considering the risks from multi-unit accidents at a site. A number of studies have developed methods for site or multi-unit risk assessment and performed the assessment using the methods [1-8]. However, it is difficult to find published research that uses a probabilistic safety assessment (PSA) model for a commercial nuclear power plant (NPP) and that considers both at-power and shutdown conditions in assessment.

In a recent study, the authors estimated the contribution to site core damage frequency (CDF) from simultaneous occurrences of independent initiators in two or more units at a site (e.g., "loss of coolant accident in Unit 1" and "general transient in Unit 2"), and it was estimated to be sufficiently low to be neglected [9].

This study aims to estimate the site CDF due to the multi-unit loss of offsite power (LOOP) initiator, one of the representative common-cause initiators affecting simultaneously two or more units at a site. It considers both at-power and shutdown conditions of each unit at a site. For this purpose, a case study was conducted on a multi-unit site with 6 OPR1000 units.

Some assumptions and methods used in this study are firstly described, and the results and conclusions of the analysis are described.

2. Methods and Results

A virtual NPP site with six OPR1000 units (i.e., 6 reactors) was considered as the reference site. The latest revisions of the at-power and low-power/shutdown (LPSD) internal events Level 1 PSA models for an OPR1000 were used as the base models for each of the 6 units.

2.1 Key Assumptions

This study is subject to the following assumptions.

1) All six units at the reference site are identical with the exception of emergency diesel generators (EDGs) and operators. That is, SSCs (structure, systems, and components) except EDGs, operating/test/maintenance procedures are the same. Therefore, the internal events Level 1 PSA model for a specific unit at the site was also used as the single-unit model for the other five units at the site.
2) For EDGs and AAC DGs (alternate AC diesel generators), the current status of the Hanul and Hanbit NPP sites each of which has 6 units was considered. It was assumed that Units 1 and 2 have the same type of EDGs and share an AAC DG and Units 3 through 6 have another same type of EDGs and share another AAC DG.
3) A "multi-unit LOOP initiating event" occurs concurrently in all 6 units. It means that the occurrence of the initiating event causes the loss of offsite power for all the units.
4) There is no dependency between operation actions in different units except offsite power recovery actions, for which "complete dependency" was assumed.
5) For units being in shutdown conditions, conditional core damage probabilities (CCDP) given a multi-unit LOOP at POS 7, 8, 9 or 12B were assumed to be zero as in the LPSD PSA for a single unit.
6) For each AAC DG shared between two or four units, the priority was given in the order of Unit 1 → Unit 2 and of Unit 3 → Unit 4 → Unit 5 → Unit 6, respectively. The time difference between station blackouts (SBOs) in each unit was not considered. In addition, if at least one unit is in a shutdown condition, it was assumed that its priority is given to a unit operating at-power.

2.2 Estimation of Multi-Unit LOOP Frequency

The multi-unit LOOP initiating event frequency was estimated based on the Korean nuclear industry data. Among the 10 site-level LOOP events (15 plant-level LOOP events) during the period 1978-2016, there were 2 LOOPs that affected all units operating at the site when the events occurred. One event affected two units but not all units at the site, and the other 7 LOOPs only occurred at one unit (i.e., single-unit LOOPs).

For a multi-unit PSA, it is most convenient to measure initiating event frequencies on a per site-year basis (not per reactor-year) [1]. A total of 141.3 site-years were obtained by summing the operating years of six NPP sites (i.e., Kori, Hanul, Hanbit, Wolsong, Shin-Kori, and Shin-Wolsong) in Korea during the period 1978-2016.

In this study, a multi-unit LOOP initiating event was assumed to occur concurrently in all six units. Therefore, only two LOOP events affecting all units at the site were used. Its mean frequency and distribution, as shown in Table I, was estimated by a Bayesian update of the Jeffreys noninformative prior with the Korean industry data [10].

Table I: Multi-unit LOOP initiating event data and frequency distribution

Data		Frequency distribution			
Number of events	Site years	Dist.	Mean	α	β
2*	141.3	Gamma	1.77E-02	2.5	141.3

* Among the 10 site-level LOOP events, only two events affecting all units at the site were used.

2.3 Estimation of Fraction of Time for Each Number of Units in Shutdown

Since this study was conducted for a site with 6 units, a maximum of 6 units can be in shutdown conditions at the same time. Therefore, when we consider both full power and LPSD conditions of each unit at a site, the site CDF can be obtained by weighting each CDF evaluated for a specific number of units in shutdown (0, 1, 2, …) by its fraction of time and summing the CDFs. The equation for the site CDF is

$$CDF_{site} = \sum_{i=0} \{ CDF_i \times FR_{NUM\_UNIT(i)} \} \qquad (1)$$

where:

i = number of units in shutdown;
CDF_i = frequency of core damage on at least one unit at a site per site year when i unit(s) is/are in shutdown; and
$FR_{NUM\_UNIT(i)}$ = fraction of time when i unit(s) is/are in shutdown (with range {0,1}).

To estimate fraction of time for each number of units in shutdown, refueling outage experiences of the Korean nuclear power plants were investigated. Maintenance outages and other unscheduled plant shutdowns (cf. [11]) were excluded because refueling outages account for over 90% of outages in Korea.

Of the 6 NPP sites in Korea, the Hanul site with 6 units was selected as a representative and its refueling outage (or overhaul) experiences during the period 2003-2015 were examined [12]. There were a total of 49 refueling outages during the period, and the average duration of refueling outages was 56.1 days. Table II shows the fraction of time for each number of units in shutdown. A maximum of 3 units at the site were in shutdown conditions at the same time. The number of days with no unit in shutdown (i.e., with all 6 units at-power) accounts for 54.0% of the period (13 years). The number of days with one unit in shutdown accounts for 34.6% and the number of days with two units in shutdown accounts for 11.0%. There were 21 days when three units were in shutdown conditions at the same time, although it is almost negligible (0.4%).

Table II: Fraction of time for each number of units in shutdown (for Hanul site)

Number of units in shutdown (overhaul)	Number of days	Fraction (%)
0	2,562	54.0
1	1,643	34.6
2	522	11.0
3	21	0.4
4~6	0	0.0
Sum	4,748	100.0

2.4 Development of Site CDF Models

To estimate the site CDF due to the multi-unit LOOP initiator, fault tree models were developed using the following steps:

1) Construction of the top logic for the site CDF models;
2) Modifications of the single-unit at-power and LPSD PSA models for integrating into the top logic;
3) Modifications of fault trees considering inter-unit dependencies;

Fig. 1 shows the top logic for a fault tree developed for estimating the site CDF due to multi-unit LOOPs. The top event corresponds to the core damage on at least one of the six units at the site.

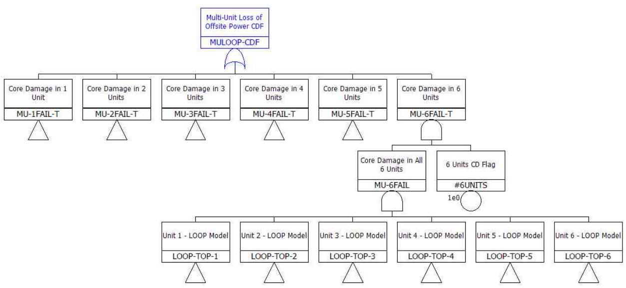

Fig. 1. Top logic for estimating the site CDF due to multi-unit LOOPs

Fig. 2 shows an example of developing a site CDF model using single-unit LOOP models for at-power and shutdown (each POS) operations. For each POS, a site CDF model as shown in Fig. 2 was developed and the frequency of core damage when only one unit is in shutdown (CDF_1 in equation (1)) was calculated by summing the weighted CDF for each POS, which can be obtained by multiplying the CDF from its model by fraction of time of each POS. For POS 7, 8, 9 and 12B, a site CDF model with only 5 units at-power was developed. The frequency of core damage when two units are in shutdown (CDF_2 in equation (1)) was estimated based on CDF_1 because it is very time-consuming to develop a site CDF model for each combination.

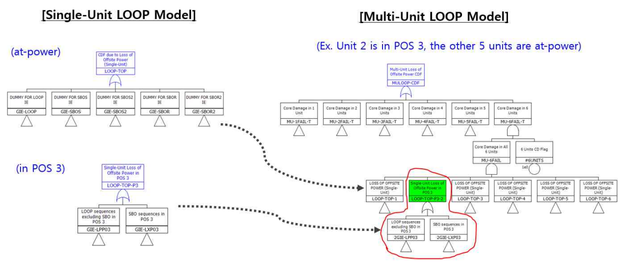

Fig. 2. An example of the site CDF model for the case where one unit at the site is in shutdown and the other 5 units are at-power.

Inter-unit dependencies were taken into account for the following aspects:

1) Structure, systems or components (SSCs) shared between multiple units;
2) Dependencies between human failure events (HFEs) in different units;
3) Inter-unit common-cause failures (CCFs)

According to a recent study on a multi-unit initiating event analysis for an OPR1000 plant [13], the sharing of an alternate AC diesel generator (AAC DG) between multiple units should be considered for the purpose of this study. In this study, it was assumed that Units 1 and 2 share an AAC DG and Units 3 through 6 share another AAC DG. It was also assumed that for each AAC DG, the priority was given in the order of Unit 1 → Unit 2 and of Unit 3 → Unit 4 → Unit 5 → Unit 6, respectively. Therefore, fault trees related to AAC DGs were modified considering these assumptions [14]. For example, in case that Units 1 and 2 experience SBO simultaneously, the AAC DG is connected only to Unit 1 and hence it is not available in Unit 2.

Although most human actions included in the single-unit Level 1 PSA model are regarded as independent from those in different units, offsite power recovery actions in units sharing a switchyard or a grid should be considered as dependent. Since this study considers a multi-unit LOOP event affecting all 6 units at the site, there is much possibility that it is a grid-related or weather-related LOOP [15]. Therefore, it was assumed that offsite power recovery actions are completely dependent between the 6 units. The same basic event for the probability of not recovering offsite power within a specific time was used for all 6 units.

For inter-unit CCFs, only CCFs of diesel generators (EDGs and AAC DGs) were considered because minimal cutsets involving failure(s) of DG(s) accounts for about 96% of the total CDF resulting from the LOOP event in the existing at-power internal events Level 1 PSA model for a single unit. According to the second assumption in Section 2.1, two different common cause component groups (CCCGs) were considered: one is for 5 DGs in Units 1 and 2; another is for 9 DGs in Units 3 through 6. For each CCCG, all CCF basic events were modeled. In cases where one or more units are in shutdown, the EDG in maintenance (EDG A in POS 3~8, EDG B in POS 9~10) was removed from its CCCG reducing the size of CCCG to 4 or 8.

For the CCF data, alpha factors for EDGs from NUREG/CR-5497 [16] were used. Because it does not provide alpha factors for more than 4 EDGs (CCCG size > 4), impact vectors for CCCG=5 and CCCG=9 were obtained using the mapping up technique [17]. In addition, a staggered testing scheme was assumed in calculating the probabilities of the CCF basic events.

2.5 Quantification Results

The quantification was performed by using the AIMS-PSA software (Rev. 1.2) [18] and the FTREX quantification engine (Ver. 1.8, 64 bit) [19].

As a result of quantification, the site CDF due to the multi-unit LOOP initiator was about 4.9E-06 per site-year. The frequency of core damage on only one unit contributed 92.9% of the total site CDF, followed by the frequency of core damage on only two units (6.3%) and the frequency of core damage on three units (0.7%). The frequency of core damage on four or more units was negligible.

3. Conclusions

In this study, the site CDF due to multi-unit LOOPs was estimated. A virtual site with 6 OPR1000 units was considered as the reference site and the at-power and low-power/shutdown internal events Level 1 PSA models for an OPR1000 unit were used as the base models. The multi-unit LOOP initiating event frequency and fraction of time for each number of units in shutdown were estimated, and fault tree models for estimating the site CDF were developed under some assumptions.

As a result, the site CDF due to the multi-unit LOOP initiator was about 4.9E-06 per site-year. The frequency of core damage on only one unit dominated the total site CDF, accounting for 92.9%.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP: Ministry of Science, ICT and Future Planning) (No. 2017M2A8A4015287).

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